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Robert Ojiambo,[1,2] Kenn Konstabel,[1,3,4] Toomas Veidebaum,[3] John Reilly,[5] Vera Verbestel,[6] Inge Huybrechts,[7] Isabelle Sioen,[7,8] José A. Casajús,[9] Luis A. Moreno,[9] German Vicente-Rodriguez,[9] Karin Bammann,[10] Bojan M. Tubić,[11] Staffan Marild,[11] Klaas Westerterp,[12] and Yannis P. Pitsiladis,[1,2] on behalf of the IDEFICS Consortium

[1]*College of Medical, Veterinary and Life Sciences, University of Glasgow, Glasgow, Scotland;* [2]*Department of Medical Physiology, Moi University, Eldoret, Kenya;* [3]*National Institute for Health Development, Tallinn, Estonia;* [4]*Institute of Psychology, University of Tartu, Tartu, Estonia;* [5]*Physical Activity for Health Group, School of Psychological Science and Health, University of Strathclyde, Glasgow, Scotland;* [6]*Departement of Movement and Sport Sciences, Ghent University, Ghent, Belgium;* [7]*Ghent University, Department of Public Health, Ghent, Belgium;* [8]*Fonds Wetenschappelijk Onderzoek, Research Foundation Flanders, Brussels, Belgium;* [9]*Faculty of Health and Sport Sciences, Growth, Exercise, Nutrition and Development (GENUD) Research Group, E.U. Ciencias de la Salud, University of Zaragoza, Zaragoza, Spain;* [10]*Bremen Institute of Prevention Research and Social Medicine, University of Bremen, Bremen, Germany;* [11]*Department of Pediatrics, Institute for Clinical Sciences, Queen Silva Children's Hospital, Sahlgrenska Academy at University of Gothenburg, Gothenburg, Sweden;* and [12]*Energy Metabolism Research Unit, Department of Human Biology, Maastricht University, Maastricht, The Netherlands*

Ojiambo R, Konstabel K, Veidebaum T, Reilly J, Verbestel V, Huybrechts I, Sioen I, Casajús JA, Moreno LA, Vicente-Rodriguez G, Bammann K, Tubić BM, Marild S, Westerterp K, Pitsiladis Y, IDEFICS Consortium. Validity of hip-mounted uniaxial accelerometry with heart-rate monitoring vs. triaxial accelerometry in the assessment of free-living energy expenditure in young children: the IDEFICS Validation Study. *J Appl Physiol* 113: 1530–1536, 2012. First published September 20, 2012; doi:10.1152/japplphysiol.01290.2011.—One of the aims of Identification and Prevention of Dietary- and Lifestyle-Induced Health Effects in Children and Infants (IDEFICS) validation study is to validate field measures of physical activity (PA) and energy expenditure (EE) in young children. This study compared the validity of uniaxial accelerometry with heart-rate (HR) monitoring vs. triaxial accelerometry against doubly labeled water (DLW) criterion method for assessment of free-living EE in young children. Forty-nine European children (25 female, 24 male) aged 4–10 yr (mean age: 6.9 ± 1.5 yr) were assessed by uniaxial ActiTrainer with HR, uniaxial 3DNX, and triaxial 3DNX accelerometry. Total energy expenditure (TEE) was estimated using DLW over a 1-wk period. The longitudinal axis of both devices and triaxial 3DNX counts per minute (CPM) were significantly ($P < 0.05$) associated with physical activity level (PAL; $r = 0.51$ ActiTrainer, $r = 0.49$ uniaxial-3DNX, and $r = 0.42$ triaxial Σ3DNX). Eight-six percent of the variance in TEE could be predicted by a model combining body mass (partial $r^2 = 71\%$; $P < 0.05$), CPM-ActiTrainer (partial $r^2 = 11\%$; $P < 0.05$), and difference between HR at moderate and sedentary activities (ModHR − SedHR) (partial $r^2 = 4\%$; $P < 0.05$). The SE of TEE estimate for ActiTrainer and 3DNX models ranged from 0.44 to 0.74 MJ/days or ~7–11% of the average TEE. The SE of activity-induced energy expenditure (AEE) model estimates ranged from 0.38 to 0.57 MJ/day or 24–26% of the average AEE. It is concluded that the comparative validity of hip-mounted uniaxial and triaxial accelerometers for assessing PA and EE is similar.

accelerometers; validity; young children; obesity; doubly labeled water.

PHYSICAL ACTIVITY (PA) IS a complex behavior that varies with age, gender, season, weekday, and time of the day and is also influenced by biological, sociological, psychological, and environmental factors (1). A decline in PA has been identified as an important contributory factor in childhood obesity (24) but is difficult to quantify precisely, as few studies utilize the same methods of assessment and limited objective data exist (1, 24). PA is generally considered to be a central factor in the etiology, prevention, and treatment of childhood obesity (37), and thus the quantification of energy expenditure (EE) and daily PA has gained considerable interest (9). However, accurate assessment of PA and sedentary behavior, especially in children remains a significant challenge (1). Consequently, validated techniques of estimating habitual PA are needed to study the relationship between free-living PA and obesity (37). These methods should be suitable to measure PA over periods long enough to be representative for normal daily life, with minimal discomfort to the subjects, and applicable to large study populations (37).

The ability to accurately track EE using objective methods is crucial (11), especially in studies that aim to track the trends in EE over time. Doubly labeled water (DLW) is the only technique available to accurately measure total energy expenditure (TEE) over prolonged periods in daily life (5). When this technique is combined with a measure of basal metabolic rate (BMR), activity-induced energy expenditure (AEE) can be calculated; i.e., $AEE = 0.9 \times TEE - BMR$ or physical activity level (PAL) $= TEE/BMR$ (19). However, since DLW is markedly expensive and requires appropriate laboratory equipment for sample analysis, it is infrequently used in large-population studies to assess TEE and related correlates. Thus

other methods such accelerometry have been proposed to assess PA and to estimate TEE (5). Accelerometers provide a means by which researchers can examine the intensity, frequency, and duration of PA bouts that individuals are performing over extensive periods of time (10). By validating an accelerometer against DLW-derived EE, prediction models can be developed to predict AEE, TEE, or PAL from accelerometer counts and other physical characteristics, such as age, sex, height, and body mass (BM; Ref. 19). Thus improvement of the accuracy of accelerometers in predicting TEE, AEE, and PAL has been the focus of several studies in adults (4, 9, 20). However, there has been less examination of the validity of accelerometers against DLW in very young children.

Uniaxial accelerometers measure accelerations in one plane (usually longitudinal axis of the body), whereas triaxial accelerometers measure accelerations in the anterior-posterior, mediolateral, and longitudinal directions (10). Although uniaxial accelerometers are accurate in the prediction of EE during walking, triaxial accelerometers were found to be more suitable when a variety of different activities are involved (6, 17, 19, 33). However, the inclusion of heart-rate (HR) monitoring may improve the quality of the data collected by uniaxial accelerometry. The most widely used and extensively validated uniaxial accelerometer for assessment of PA among children is the ActiGraph (ActiGraph, Pensacola, FL) accelerometer (11, 15). The ActiTrainer is a recent ActiGraph uniaxial accelerometer with the capability to measure body acceleration and HR as well. On the other hand, the capability of the triaxial 3DNX (BioTel Limited, Bristol, UK) accelerometer to predict EE in free-living adult and adolescent cohorts has also been examined using the DLW method as a criterion measure (8).

These authors did not find any association between 3DNX outputs and PAL or AEE scaled to body mass, which are parameters directly related to PA (8). The purpose of this study, therefore, was to examine the comparative validity of the novel uniaxial ActiTrainer with HR monitoring; uniaxial 3DNX ($3DNX_x$, $3DNX_y$, and $3DNX_z$) and triaxial 3DNX ($\Sigma 3DNX_{xyz}$) accelerometers against DLW criterion during free-living activities in young children.

MATERIALS AND METHODS

Subjects. Ninety-six children were recruited from four validation centers at the universities of Glasgow (UK), Ghent (Belgium), Gothenburg (Sweden), and Zaragoza (Spain). The general protocol and main general findings have been described elsewhere (2). Forty-nine children from the initial cohort (25 female, 24 male) aged between 4–10 yr (mean age 6.9 ± 1.5 yr: Table 1) fulfilled the inclusion criteria for final data analysis, i.e., at least 6 days including at least 1 weekend day of valid recording of at least 600 min of continuous monitoring per day as recommended in previous studies (18, 30). In addition, subjects were required to have concurrent ActiTrainer, HR, and 3DNX recording. The data from the two devices could not be exactly aligned because 3DNX is started manually by pressing a button, and therefore the exact start time cannot be preset unlike the case with the ActiTrainer. The resulting difficulty was not foreseen when the study was carried out: otherwise, one could have manually started the 3DNX exactly at the time when the ActiTrainer was initialized. Retrospectively, the only thing we could do is to summarize the data by longer periods (in this case, 30 min) and keep only those periods that have complete data for both devices.

Thus 34,545 h (in 30-min bouts) were initially matched. Subsequently, only 11,791 h remained after deletion of noncompliant

Table 1. *Descriptive characteristics of subjects*

Parameter	Means ± SD	Range
Age, yr	6.9 ± 1.5	(4–10)
Weight, kg	24.7 ± 6.6	(14–48)
Height, cm	122 ± 9.5	(100.5–140)
BMI, kg/m²	16.6 ± 3.0	(13.6–26)
BMR, MJ/day	4.3 ± 0.6	(3.2–6.0)
TEE, MJ/day	6.6 ± 1.2	(3.9–10.3)
AEE, MJ/day	1.6 ± 0.6	(0.3–3.4)
PAL	1.5 ± 0.1	(1.2–1.8)
CPM-ActiTrainer	587 ± 121	(310–880)
CPM-Σ3DNX$_{xyz}$	816 ± 120	(562–1104)
Monitoring time, min	720 ± 46	(619–819)

Values are means ±SD; $n = 49$ (24 males; 25 females). BMI, body mass index; BMR, basal metabolic rate; TEE, total energy expenditure; AEE; activity-induced energy expenditure; PAL, physical activity level; CPM-ActiTrainer, counts per minute of uniaxial ActiTrainer accelerometer; CPM-Σ3DNX$_{xyz}$, counts per minute of triaxial sum of 3DNX accelerometer.

periods [i.e., where some nonwear time (≥20 min of consecutive zeroes) was detected by at least one of the monitors]. This period of consecutive zeroes was reported to be inconsistent with monitor wear in children (29). Median of wear time was 668 min, with the interquartile range of 76 min. Written informed consent was obtained from parents. Ethical approval for the study was granted by the respective ethical committees of each of the four centers. Height was measured to the nearest 0.1 cm using a portable stadiometer (Seca 225; Seca, Hamburg, Germany) and BM was measured (to 0.1 kg) using an electronic balance (TANITA BC 420 SMA; TANITA Europe, Sindelfingen, Germany) for all children and used to calculate body mass index (BMI).

Assessment of EE. TEE was measured with DLW according to the Maastricht protocol (36). In short, after the collection of a base-line urine sample (*day 0*), subjects drank a weighed amount of $^2H_2{}^{18}O$ resulting in an initial excess body water enrichment of 125–150 ppm for deuterium and 250–300 ppm for oxygen-18. Subsequent urine samples were collected from the second voiding in the morning and a subsequent voiding in the evening on *days 1*, *4*, and *8*. Urine samples were stored at −4°C in cryogenically stable tubes until analysis by isotope ratio mass spectrometry. Samples were analyzed in duplicate for H_2O^{18} and ^2H_2O at the Department of Human Biology at Maastricht University (Maastricht, The Netherlands). Carbon dioxide production rate was estimated from the differential disappearance of the two isotopes using equation A6 of Schoeller et al. (26) and was converted to EE using the de Weir equation (12), assuming an average diet resulting in a respiratory exchange ratio of 0.85 (3). The Schofield equations (27) based on gender, age, height, and weight were used to predict BMR for subjects aged 3–10 yr as described as follows: BMR (kcal/day) = 19.59 BM + 1.303 H + 414.9 (males) and BMR (kcal/day) = 16.969 BM + 1.618 H + 371.2 (females), where BM is body mass in kilograms and H is height in centimeters. These equations have been identified as those showing the best agreement with measured BMR in young children and adolescents (25).

Accelerometry. Free living daily PA levels and patterns were objectively assessed using the uniaxial ActiTrainer accelerometer (ActiGraph). The monitor was set to record PA in a 15-s epoch. The ActiTrainer is surrounded by a metal shield and packaged into a plastic enclosure measuring 50 × 40 × 15 mm, weighs ~45 g including a 3 -V (2,430) coin cell lithium battery, has a dynamic range of 0.25 to 2.5 *g*, a sampling frequency of 30 Hz, and contains a cantilevered rectangular piezoelectric bimorph plate and seismic mass, a charge amplifier, analog band-pass filters, and a voltage regulator to measure acceleration in a single axis. The filtered acceleration signals (in the longitudinal axis) generate counts the magnitude of which is summed over a user-specific time (an epoch interval). At the end of each epoch, the summed value is stored in memory and

the numerical integrator reset. The 3DNX model v3 (BioTel Limited, Bristol, UK; www.biotel.co.uk) is sensitive to movements in three planes: x (antero-posterior), y (mediolateral), and z (longitudinal). The unit measures $54 \times 54 \times 18$ mm and weighs 70 g including a 3.6-V lithium battery (Saft). Approximately 21 days of data can be stored when collecting at 15-s intervals. The unit contains two ADXL321 biaxial microelectromechanical (MEMS) sensors (Analog Devices, Surrey, UK) positioned orthogonally to measure acceleration in three movement planes. Data for each axis were amplified and filtered (0.11 Hz high pass, 20 Hz low pass) to attenuate the DC responses and the sum of the rectified and integrated acceleration curves for the three axes measured.

Physical activity assessment. Subjects wore the accelerometers for 7 consecutive days between January and April 2009 during school term time simultaneous with the DLW measurements. Accelerometers were mounted on the right hip of each child on the same elastic belt and adjusted to ensure close contact with the body. However, accelerometer placement on the right hip was not randomized. In addition, all subjects were fitted with a HR transmitter belt (Suunto t6; Suunto Oy, Vantaa, Finland) on the chest to record HR continuously. The subjects were required to wear the accelerometers and HR transmitter belts from the moment they woke up in the morning until bed time in the evening so that a full day of PA could be assessed. In addition, accelerometers and HR transmitter belts had to be removed for aquatic activities.

Accelerometer and HR data reduction. Accelerometer data were analyzed using algorithms developed in R (version R 2.9.0.; R Foundation for Statistical Computing, Vienna, Austria; http://www.R-project.org; Ref. 23). A set of add-on functions to R was developed that allowed R to automatically read in the accelerometer raw files; reintegrate any data collected in 5-s epoch to 15 s to standardize epoch settings, edit the data for excluding the likely nonwearing periods and compute daily summary statistics. Two rules were used for excluding data: *1*) all negative counts were replaced by missing data code and *2*) periods of 20 min or more consecutive zero counts were replaced by missing data code before further analysis. The output generated by R included accelerometer counts per day (CPM) and total monitoring time and time spent sedentary and in physical activities of different intensities based on Evenson cut points (14) and HR data (minimal HR, maximal HR, and mean HR). In addition, the difference in HR during moderate and sedentary activity, i.e., (ModHR − SedHR) was also computed based on accelerometer outputs.

Data analysis. Descriptive statistics included means, SD, or (range) following a Shapiro-Wilk test for normality. To identify the relationship between total volume of PA as evaluated by CPM (uniaxial and triaxial) and TEE, AEE, and PAL, hierarchically nested regression models were used. The regression models for TEE, AEE, and PAL included, BM, CPM-ActiTrainer (ModHR − SedHR), and CPM-3DNX (uniaxial and triaxial) as independent variables. Nonlinear models were also explored (i.e., square of body mass and square of CPM), as well as log-transforming predictor and response variables. For all reported models, the appropriateness of identity link function was checked as recommended by Pregibon (21), all models passed the test indicating that a linearizing transformation was not necessary. In addition, the Box and Tidwell (7) test indicated no departures from linearity in the relationship between BM and EE. Nevertheless, this relationship is theoretically best conceptualized as allometric (38); for comparison, we calculated allometric scaling coefficients using ordinary least squares regression i.e., TEE and AEE scaled to the body mass raised to the powers of 0.63 and 1.10, respectively. Leave-one-out cross-validation was used to calculate prediction errors (PE). To do this, each regression model was fitted N times, with each participant excluded one at a time, and the dependent variable was predicted for the excluded participant. The PE was calculated as mean squared difference between predicted values from cross-validation analyses and the actual values of the dependent variable. Two ways of treating nonwear time were explored ACC_1, where nonwear time was treated

as average activity for each subject, and ACC_0, where nonwear time was treated as no activity. Significance was set at $P < 0.05$. The statistical analyses were completed using the software package SPSS, version 17.0 (SPSS, Chicago, IL), and R version 2.14.1 (23).

RESULTS

The descriptive statistics of the subjects are presented in Table 1. There was no significant difference in age, gender, and BM between the 49 subjects with complete accelerometer, HR, and EE data included in the study and the 47 with incomplete data that were excluded from the study. Subjects wore both accelerometers for an average of 720 ± 46 min and range of 619–819 per day. Measured TEE and calculated AEE and PAL are presented in Table 1. None of the CPM-ActiTrainer, CPM-$3DNX_z$, or CPM-$\Sigma 3DNX_{xyz}$ was significantly correlated with TEE and AEE ($P > 0.05$; Fig. 1). On the other hand, CPM-ActiTrainer, CPM-$3DNX_z$, and CPM-$\Sigma 3DNX_{xyz}$ were significantly ($P < 0.05$) correlated with PAL ($r = 0.47$, $r = 0.42$, and $r = 0.38$ for CPM-ActiTrainer, CPM-$3DNX_z$, and CPM-$\Sigma 3DNX_{xyz}$, respectively; Fig. 2).

TEE prediction models using uniaxial and triaxial accelerometer outputs. 86% of the variance in TEE could be predicted by a model combining BM (partial $r^2 = 71\%$; $P < 0.05$), CPM-ActiTrainer (partial $r^2 = 11\%$; $P < 0.05$), and (ModHR − SedHR) (partial $r^2 = 4\%$; $P < 0.05$; Table 2). Similarly, 79% of the variance in TEE could be predicted by a model combining BM (partial $r^2 = 71\%$; $P < 0.05$) and CPM-$\Sigma 3DNX_{xyz}$ (partial $r^2 = 8\%$; $P < 0.05$) (Table 2). However, a model examining the predictive validity of the individual 3DNX axes indicated that 81% of the variance in TEE could be predicted by BM (partial $r^2 = 71\%$; $P < 0.05$) and $3DNX_z$ (partial $r^2 = 10\%$; $P < 0.05$). Addition of $3DNX_x$ and $3DNX_y$ improved the model R^2 by 3%, which was not significant ($P > 0.05$; Table 2). The SEE of TEE estimate for ActiTrainer and 3DNX models ranged from 0.44 to 0.74 MJ/day or ∼7–11% of the average TEE (Table 2). Height, age, and gender and other HR variables were not significant predictors of TEE in our cohort. Furthermore, adding quadratic terms of any of the predictors to any of the models did not result in significant improvement of fit. However, log transformation decreased model R^2 by approximately ≤2%. PE for all TEE models are shown in Table 2.

AEE prediction models using uniaxial and triaxial accelerometer outputs. Sixty-one perecent of the variation in AEE could be explained by BM (partial $r^2 = 35\%$; $P < 0.05$), CPM-ActiTrainer (partial $r^2 = 22\%$; $P < 0.05$), and (ModHR − SedHR) (partial $r^2 = 4\%$: $P < 0.05$; Table 3). Similarly, 51% of the variance in AEE could be predicted by BM (partial $r^2 = 35\%$; $P < 0.05$) and CPD-$\Sigma 3DNX_{xyz}$ (partial $r^2 = 16\%$; $P < 0.05$; Table 3). However, a model examining the predictive validity of individual 3DNX axes indicated that 55% of the variance in AEE could be predicted by BM (partial $r^2 = 35\%$; $P < 0.05$) and $3DNX_z$ (partial $r^2 = 20\%$; $P < 0.05$). Addition of $3DNX_x$ and $3DNX_y$ improved the model R^2 by 3%, but this contribution was not significant ($P > 0.05$). The SE of AEE estimates ranged from 0.38 to 0.57 MJ/day or 24–26% of the average AEE for the CPM-ActiTrainer and CPM-3DNX models respectively (Table 3). Height, age, and gender were not significant predictors of AEE in our cohort. Furthermore, adding quadratic terms of any of the predictors to any of the models did not result in significant improvement of fit. How-
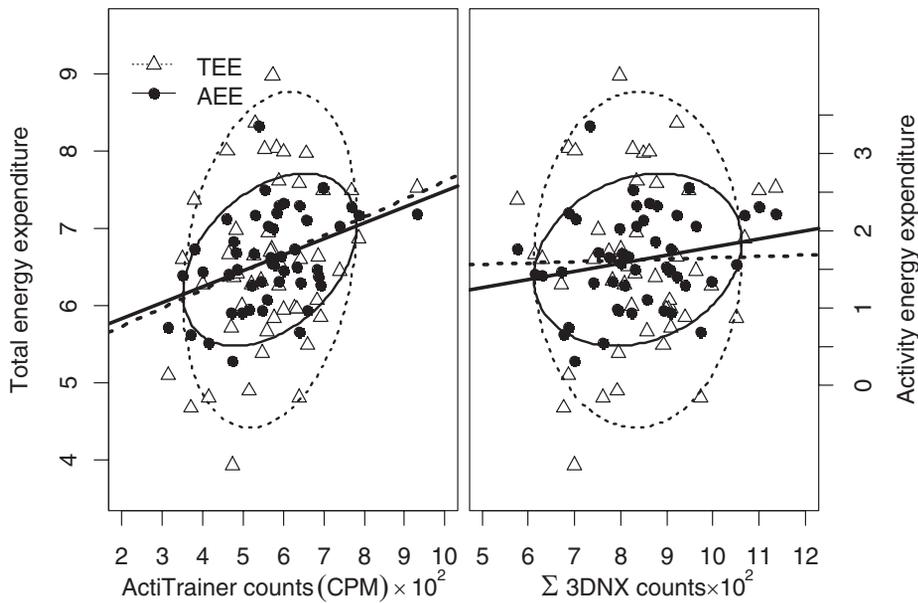
Fig. 1. Relationship of ActiTrainer and 3DNX accelerometer outputs with total energy expenditure (TEE) and activity-induced energy expenditure (AEE) (with linear regression lines and 80% prediction data ellipses) in 4- to 10-yr-old children. Under bivariate normality, the percentage of observations falling inside the ellipse should closely agree with the specified confidence level. Data ellipse collapses diagonally as the correlation between two variables approaches 1 or −1. Data ellipse is more circular when two variables are uncorrelated.

ever, log transformation improved model R^2 by ≤2%. PE for all AEE models are shown in Table 3.

DISCUSSION

EE can be estimated by measuring body acceleration (39). The DLW and indirect calorimetry that measures oxygen uptake, carbon dioxide production, and cardiopulmonary parameters are regarded as the gold-standard references of EE (39). Although accurate, gas analyzers for indirect calorimetry are expensive and they require specialized skills to operate (39). Therefore, accelerometers provide an alternative method of estimating EE in a free-living environment (4). In the current study, ActiTrainer with HR monitoring and 3DNX reported comparable model prediction accuracy for free-living TEE and AEE with similar models obtained with the Tracmor$_D$ accelerometer in adults (5) based on reported SEE and partial r^2 values. Furthermore, Carter et al. (8) developed a model to

predict TEE using as independent variables body height and activity counts as measured with the 3DNX accelerometer and found no association between accelerometer outputs and PAL, which is directly related to PA. In our study cohort on the other hand, uniaxial ActiTrainer and 3DNX$_z$ reported comparable validity relative to triaxial 3DNX accelerometer (Tables 2 and 3). Furthermore, there was significant positive association between ActiTrainer and 3DNX outputs and PAL (Fig. 2), which contradict the findings of Carter et al. (8) and is probably due to the fact that they used an earlier generation of the 3DNX accelerometer; lower subject numbers, i.e., 37 compared with 49 in the current study or sample-specific differences between the two studies.

A previous study in children indicated that activity counts from the CSA ActiGraph activity monitor contributed significantly to the explained variation in TEE and AEE in children (13). Similarly, the ActiTrainer ActiGraph accelerometer out-
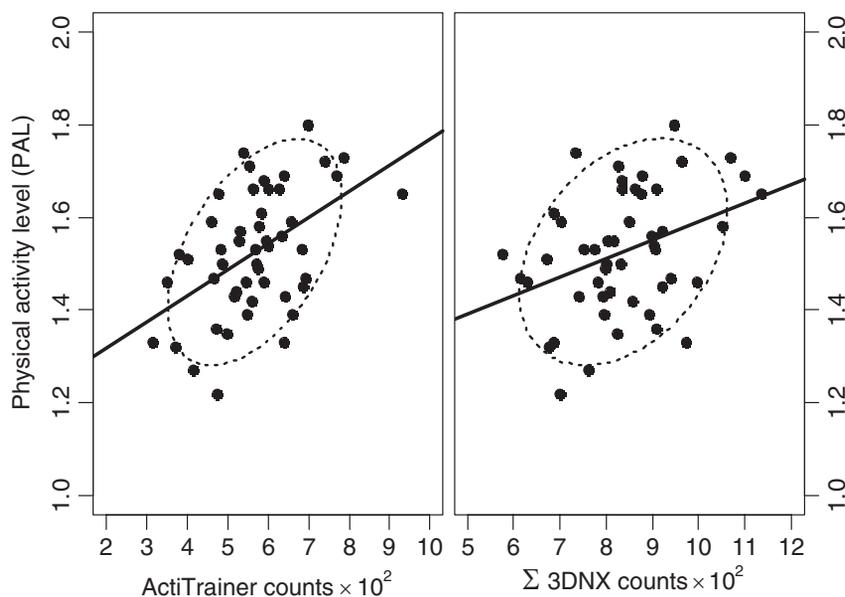

Fig. 2. Relationship of ActiTrainer and 3DNX accelerometer outputs with physical activity level (PAL; with linear regression lines and 80% data ellipses) in young children. Under bivariate normality, the percentage of observations falling inside the ellipse should closely agree with the specified confidence level. Data ellipse collapses diagonally as the correlation between two variables approaches 1 or −1. Data ellipse is more circular when two variables are uncorrelated.

Table 2. *Comparison of the accuracy of TEE prediction models using body mass plus uniaxial with heart rate vs. triaxial accelerometry*

Model	R^2	Δr^2	SEE	PE	P
BM	71%		0.37	0.43	$P < 0.05$
BM + ActiTrainer	82%	11%	0.49	0.28	$P < 0.05$
BM + ActiTrainer + (ModHR − SedHR)	86%	15%	0.44	0.23	$P < 0.05$
BM + 3DNX$_z$	81%	10%	0.64	0.33	$P < 0.05$
BM + 3DNX$_z$ + 3DNX$_x$	81%	10%	0.71	0.29	$P < 0.05$
BM + 3DNX$_z$ + 3DNX$_x$ + 3DNX$_y$	83%	12%	0.71	0.30	$P < 0.05$
BM + $\sum$3DNX$_{xyz}$	79%	8%	0.74	0.29	$P < 0.05$

CPM-ActiTrainer, counts per minute of uniaxial ActiTrainer accelerometer contribution to the regression coefficient; CPM-3DNX$_z$, counts per minute of z-axis (longitudinal) contribution to the regression coefficient; CPM-3DNX$_x$, counts per minute of x-axis (anteroposterior) contribution to the regression coefficient ; CPM-3DNX$_y$, counts per minute of y-axis (mediolateral) contribution to the regression coefficient; CPM-$\sum$3DNX$_{xyz}$, counts per minute of triaxial sum of 3DNX accelerometer contribution to the regression coefficient; (ModHR − SedHR), difference in HR during sedentary and moderate activities; Δr^2, change in R^2 relative to the first model containing body mass as the single predictor; TEE, total energy expenditure; BM, body mass; SEE, standard error of estimate; PE, prediction error.

puts were a significant predictor of EE in young children in the current study. Furthermore, addition of HR monitoring improved the predictive validity of the ActiTrainer. This contradicts the finding that activity measured using ActiGraph accelerometers is not related to AEE and PAL, and thus ActiGraph accelerometers may not be useful in predicting AEE in children (16). Examination of the validity of the models combining accelerometer outputs (CPM) and anthropometric measures to predict TEE, AEE, and PAL consistently indicated that uniaxial ActiTrainer outputs combined with HR monitoring were comparable to triaxial 3DNX outputs. However, comparison of our findings with previous prediction models is difficult because of differences in the activity profiles between study groups, different independent variables included in the regression such as fat free mass and sleeping metabolic rate, different age groups (5), and different devices used in other studies and other sample-specific differences.

This notwithstanding, use of accelerometer outputs to predict EE shows significant promise if accelerometer prediction accuracy of EE is improved by addressing specific issues related to accelerometer-based measurements of PA, such as intraindividual variability in AEE (5), interindividual variability in accelerometer outputs in subjects performing standardized activities (33), and lack of comparability between accelerometer counts from different manufacturers (10). However, recently van Hees et al. (32) used the GENEA (Unilever Discover, UK) accelerometer that has capability to record raw accelerometer data in g units, and therefore, this device may be practical in attempts to standardize accelerometer outputs. Most devices, however, such as the ActiTrainer and 3DNX, used in this study do not have sufficient memory to store several days worth of raw data in g units. Furthermore, the raw data are already processed into counts using proprietary algorithms and technically there is no way of converting counts back to the original g units; hence interdevice comparison of counts may not be feasible.

According to Trost et al. (31), evidence indicates that some accelerometers may perform better than others under certain conditions, but the reported differences are not consistent or sufficiently compelling to single out one brand or type of accelerometer as being superior to the others. When it comes to selecting an accelerometer, issues of affordability, product reliability, monitor size, technical support, and comparability with other studies may be equally as important as the relative validity and reliability of an instrument. It is necessary to begin systematically evaluating the absolute and concurrent validity of these instruments under a variety of conditions. This can be accomplished only by comparing multiple instruments under the same conditions and against a suitable "gold standard" (33) since the relative validity and interinstrument reliability of a given accelerometry product is of primary importance. Moreover, accelerometer validation studies should report both r^2 and SEE values, as these two parameters complement each other and facilitate comparison across studies.

Uniaxial accelerometry with HR monitoring and triaxial accelerometry were comparable in the assessment of free-living EE in young children. This is consistent with previous studies (22, 33) but contradicts the findings of Plasqui et al. in adults (19), who reported that to measure the wide variety of daily life activities triaxial accelerometers are more suitable than uniaxial. Intuitively, it is expected that the sum of body accelerations in the three axes would be a better predictor of EE associated with motion. Therefore, triaxial accelerometers in general clearly provide more information that could provide

Table 3. *Comparison of the accuracy of AEE prediction models using body mass plus uniaxial accelerometry and heart rate vs. triaxial accelerometry*

Model	R^2	Δr^2	SEE	PE	P
BM	35%		0.28	0.26	$P < 0.05$
BM + ActiTrainer	57%	22%	0.4	0.18	$P < 0.05$
BM + ActiTrainer + (ModHR − SedHR)	61%	26%	0.38	0.18	$P < 0.05$
BM + 3DNX$_z$	55%	20%	0.5	0.20	$P < 0.05$
BM + 3DNX$_z$ + 3DNX$_x$	56%	21%	0.56	0.19	$P < 0.05$
BM + 3DNX$_z$ + 3DNX$_x$ + 3DNX$_y$	58%	22%	0.57	0.19	$P < 0.05$
BM + $\sum$3DNX$_{xyz}$	51%	16%	0.56	0.20	$P < 0.05$

marginal improvements in validity in other samples (e.g., older children, more active, more diverse/complex activities besides occasional walking). However, this was not the case for the 3DNX accelerometer in our cohort, since only the longitudinal axis was a significant predictor of EE.

This study had several limitations; firstly, EE and PA are distinct constructs, which may limit attempts to validate PA measures against EE (28). Consequently, correlation between accelerometer output and DLW-derived EE measures, such as AEE or PAL are often poor and mainly determined by the subject's characteristics such as BM, age, sex, and height (19) and even the activity profiles of the study population. Secondly, it is unclear how the performance of uniaxial and triaxial accelerometry observed in the present study may generalize in other settings since they may be sample or device specific; thus further enquiry is warranted in other free-living populations.

To conclude, hip-mounted uniaxial accelerometry with HR monitoring and triaxial accelerometry have comparable validity in assessing free-living EE in young children. Uniaxial ActiTrainer and triaxial 3DNX were valid for assessing EE in young children. Furthermore, addition of HR monitoring improved the predictive validity of accelerometry. However, there is a wide array of activity monitors that have yet to be properly validated, and therefore, accuracy of most remains to be determined.

STATEMENT OF ETHICS

We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during this research. Approval by the appropriate Ethics Committees was obtained by each of the four centers at the universities of Glasgow (UK), Ghent (Belgium), Gothenburg (Sweden), and Zaragoza (Spain) doing the field work. Study children did not undergo any procedure before both they and their parents had given consent for examinations, collection of samples, subsequent analysis, and storage of personal data and collected samples.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

Author contributions: R.O., K.K., T.V., V.V., I.S., J.A.C., K.B., K.W., and Y.P.P. analyzed data; R.O., K.K., T.V., J.R., V.V., J.A.C., K.B., B.M.T., S.M., K.W., and Y.P.P. interpreted results of experiments; R.O. and Y.P.P. prepared figures; R.O., K.K., T.V., I.H., I.S., and Y.P.P. drafted manuscript; R.O., K.K., T.V., J.R., V.V., I.H., I.S., J.A.C., L.A.M., G.V.-R., K.B., and Y.P.P. edited and revised manuscript; T.V., J.R., I.H., I.S., L.A.M., K.B., B.M.T., S.M., K.W., and Y.P.P. conception and design of research; T.V., J.R., V.V., I.H., I.S., J.A.C., L.A.M., G.V.-R., K.B., B.M.T., S.M., K.W., and Y.P.P. approved final version of manuscript; I.H., I.S., J.A.C., L.A.M., G.V.-R., K.B., B.M.T., S.M., and Y.P.P. performed experiments.

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